

Determining weak phase γ and probing new physics in $b \rightarrow s$ transitions from $B \rightarrow \eta^{(\prime)} K$

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Abstract

We present a method of determining weak phase γ in the Cabibbo-Kobayashi-Maskawa matrix from decays $B \rightarrow \eta K, \eta' K$ alone. Given a large ratio between color-suppressed and color-allowed tree diagrams extracted from global $\pi\pi(K)$ fits, γ is determined from the current data of $\eta' K$ and the result is in agreement with the global Standard Model(SM) fits. However, a smaller ratio from factorization based calculations gives $\gamma \sim 90^\circ$. New physics beyond the SM can be singled out if γ obtained in $\eta^{(\prime)} K$ modes is significantly different than the ones from other modes or other approaches. The effective value of γ from $\eta' K$ is very sensitive to new physics contributions and can be used to extract new physics parameters for a class of models which do not give contributions to strong phases significantly.

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I. INTRODUCTION

Precisely obtaining the weak phase α , β and γ in the Cabibbo-Kobayashi-Maskawa (CKM) matrix is one of the central issues in the current studies of B decays. Besides global fits to all the indirect measurements in the Standard Model (SM)[1, 2] or measurements on the time-dependent CP asymmetry in $B \rightarrow J/\psi K_S$, the phase angles α and γ of the unitarity triangle can also be probed from hadronic charmless B decays. In the charmless decay modes $B \rightarrow PP$ with P denoting a pseudo-scalar final state, the weak phase γ can be determined either with theoretical inputs such as QCD factorization [3, 4], perturbation QCD [5, 6, 7] and soft-collinear effective theories [8, 9, 10] etc, or through model independent phenomenological methods based on flavor SU(3) symmetry [11, 12, 13, 14, 15, 16, 17, 18].

Within the flavor SU(3) symmetry, direct B decay amplitudes are described by a set of flavor topological diagrams. The leading diagrams involve: a tree diagram \mathcal{T} , a color suppressed tree diagram \mathcal{C} , a flavor octet (singlet) QCD penguin diagram $\mathcal{P}(\mathcal{S})$ and a color allowed (color-suppressed) electroweak penguin diagram \mathcal{P}_{EW} (\mathcal{P}_{EW}^C) etc. The hierarchical structure in the size of these diagrams simplifies the analysis and makes it powerful in exploring the hadronic B decays. Recent global fits using the diagrammatic method have already shown that the weak phase γ can be determined with a reasonable precision and the obtained value agrees well with the one from the global CKM fit [19, 20, 21, 22, 23, 24, 25].

However, the current data also exhibit some puzzling patterns which needs further understanding. The unexpected large branching ratio of $\pi^0\pi^0$ and the relative suppression of $\pi^+\pi^-$ possess a big theoretical challenge and may require large nonfactorizable contributions[26, 27, 28]; the relative enhancement of $\pi^0\bar{K}^0$ to π^+K^- may lead to an enhancement of electroweak penguin which could be a signal of new physics (see, eg. [24, 25, 26, 27, 28, 29, 30]). The recently measured mixing-induced CP asymmetries of $(\omega, \phi, \pi^0, \eta')K_S$ though not conclusive yet, suggest a possibility that the weak phase β obtained from $b \rightarrow s$ penguin-dominant processes may deviate from the one determined from $b \rightarrow c$ tree-dominated process $J/\psi K_S$ [31, 32, 33].

The global fit to all the charmless B decay modes connected by flavor SU(3) symmetry is the most consistent way to explore the weak phases and the involved hadronic decay amplitudes. However, to get more insight on the potential inconsistencies in the theory and a better understanding of the strong dynamics in hadronic B decays it is usefully to

divide the whole decay modes into several subsets in which the relevant parameters can be investigated individually. The comparison among the same quantities obtained from different subsets will not only provide us important cross-checks but also shed light on the origins of those puzzles and possible signals of new physics beyond the SM.

For instance, in $\pi\pi$ system the three decays modes $\pi^+\pi^-$, $\pi^0\pi^0$ and $\pi^0\pi^-$ provide at most seven independent observables including three branching ratios, two direct CP asymmetries (the direct CP asymmetry for $\pi^0\pi^-$ is predicted to be vanishing in SM) and two mixing-induced CP asymmetries, enough to determine the involved hadronic amplitudes \mathcal{T} , \mathcal{C} , \mathcal{P} and also the weak phase γ . In $\pi\pi$ modes, the electroweak penguins are small and negligible. The recent fits taking weak phase β as input show a good determination of all the amplitudes. The ratio of \mathcal{C}/\mathcal{T} is found to be large close to 0.8[23, 24, 25, 34, 35, 36], the weak phase γ is determined up to a multi-fold ambiguity and one of them agrees well with the SM global fit value $\sim 62^\circ$. In πK system, the available data involve four CP averaged branching ratios, three direct CP asymmetries (the direct CP asymmetry in $B^- \rightarrow \pi^- \bar{K}^0$ is predicted to be nearly zero when annihilation diagram is negligible). Plussing a mixing-induced CP asymmetry in $B \rightarrow \pi^0 K_S$, there are eight data points in total. The independent flavor diagrams include \mathcal{T} , \mathcal{C} and \mathcal{P} . The electro-weak penguin \mathcal{P}_{EW} is significant but can be related to tree type diagrams in the SM [37, 38]. Other parameters in the CKM matrix elements can be chosen as angles γ and β or the Wolfenstein parameter ρ and η . Thus the shape of the whole unitarity triangle can be in principle determined in πK modes alone[39]. The current data of πK are not enough to perform such an independent determination. Taking the SM value of weak phase γ and β as inputs, one can extract other hadronic amplitudes. The recent fits show a even larger value of $\mathcal{C}/\mathcal{T} \sim 1.7$ and enhancement of \mathcal{P}_{EW} [25, 40].

In the present paper, we discuss the determination of γ from an other important subset, the $\eta^{(\prime)}K$ modes. The advantages of using $\eta^{(\prime)}K$ final states over the $\pi\pi$ and πK states are as follows

- All the four $\eta^{(\prime)}K$ modes are penguin dominant with appreciable tree-penguin interferences. Nonvanishing direct CP asymmetries are expected in *all* the four decay modes, while in $\pi\pi(\pi K)$ one of the direct CP asymmetry in $\pi^-\pi^0(\pi^-\bar{K}^0)$ is predicted to be nearly zero.

- The two neutral modes in $\eta^{(\prime)}K$ will provide two additional data points from mixing-induced CP asymmetries in $\eta^{(\prime)}K_S$, while in πK there is only one.
- Most importantly, the flavor topological structure in $\eta^{(\prime)}K$ amplitudes allows a regrouping of penguin type diagrams in such a way that the number of independent hadronic amplitudes can be reduced to four complex parameters.
- The electroweak penguin diagram \mathcal{P}_{EW} can be included in the reduced hadronic parameters. It is not necessary to assume the SM relation between electroweak penguin and tree type diagram. This is of particular importance as the current data imply the possibility of new physics beyond the SM.

Thus in $\eta^{(\prime)}K$ modes there will be at most ten observables available, enough to simultaneously determine all the involved diagrammatic amplitudes, the weak phase γ and β which determine the apex of the unitarity triangle. This method distinguishes itself from the previous ones in that it makes use of the $\eta^{(\prime)}K$ modes *alone* while the previous methods focus on constructing quadrangles connecting to πK modes using SU(3) symmetry[16, 41].

This paper is organized as follows, in section II, we present details of determining weak phase γ from $\eta^{(\prime)}K$ modes. In section III, the implications from the current data of $\eta'K$ is discussed. We take typical values of hadronic parameters as inputs to constrain γ from $\eta'K$ modes. In section IV, the new physics effects on the γ determination is discussed. We finally conclude in section V.

II. DETERMINING γ FROM $\eta^{(\prime)}K$

We assume flavor SU(3) symmetry and take the following diagrammatic decomposition for $B \rightarrow \eta^{(\prime)}K$ decay amplitudes [42].

$$\begin{aligned}
\bar{\mathcal{A}}(\eta\bar{K}^0) &= \frac{1}{\sqrt{3}}(\mathcal{C} + \mathcal{P}_\eta), \\
\bar{\mathcal{A}}(\eta'\bar{K}^0) &= \frac{1}{\sqrt{6}}(\mathcal{C} + \mathcal{P}_{\eta'}), \\
\bar{\mathcal{A}}(\eta K^-) &= \frac{1}{\sqrt{3}}(\mathcal{T} + \mathcal{C} + \mathcal{P}_\eta), \\
\bar{\mathcal{A}}(\eta' K^-) &= \frac{1}{\sqrt{6}}(\mathcal{T} + \mathcal{C} + \mathcal{P}_{\eta'}),
\end{aligned} \tag{1}$$

which corresponds to the flavor contents of $\eta = (-s\bar{s} + u\bar{u} + d\bar{d})/\sqrt{3}$ and $\eta' = (2s\bar{s} + u\bar{u} + d\bar{d})/\sqrt{6}$ respectively. This is in accordance with an $\eta_8 - \eta_0$ mixing angle of $\theta = \arcsin(-1/3) \simeq -19.5^\circ$ [42]. Such a simple mixing scheme is a good approximation in phenomenology and is extensively used in the recent analyses of hadronic B and D decays [43, 44, 45, 46]. The two penguin type diagram are given by

$$\begin{aligned}\mathcal{P}_\eta &\equiv \mathcal{S} + \frac{2}{3}\mathcal{P}_{EW}, \\ \mathcal{P}_{\eta'} &\equiv 3\mathcal{P} + 4\mathcal{S} - \frac{1}{3}\mathcal{P}_{EW}.\end{aligned}\tag{2}$$

In the above expressions we assume that the color-suppressed electro-weak penguin \mathcal{P}_{EW}^C and annihilation diagram \mathcal{A} are small and negligible. We shall also assume the t -quark dominance in the penguin diagrams. With these assumptions, all the decay amplitudes depend on four complex parameters $\mathcal{C}, \mathcal{T}, \mathcal{P}_\eta$ and $\mathcal{P}_{\eta'}$. The two weak phases γ and β enter the expressions from direct and mixing-induced CP asymmetries as additional free parameters. Removing a overall strong phase, there are 9 real free parameters to be determined by 10 observables in $B \rightarrow \eta^{(\prime)} K$ modes which include four CP averaged decay rates, four direct CP asymmetries and two mixing-induced CP asymmetries in $\eta^{(\prime)} K_S$. Although the expressions of \mathcal{P}_η and $\mathcal{P}_{\eta'}$ depends on $\eta - \eta'$ mixing scheme, the isospin symmetry guarantees that neutral($\eta(\eta')\bar{K}^0$) and charged ($\eta(\eta')K^-$) modes have the same coefficients for \mathcal{S}, \mathcal{P} and also \mathcal{P}_{EW} , which allows the reduction to a single penguin type parameter. Thus the number of free parameters is the same for other mixing schemes such as FKS and two-mixing angle schemes (see, e.g. [47, 48]).

The CP averaged branching ratio is defined through

$$Br \equiv \frac{1}{2}\tau(|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2),\tag{3}$$

where the factor τ stands for the life time difference in B mesons and is normalized to $\tau = 1(\tau_+/\tau_0)$ for neutral(charged) modes with $\tau_0(\tau_+)$ the life time for neutral (charged) B mesons and $\tau_+/\tau_0 = 1.086$. The definition of direct CP asymmetry is

$$a_{cp} \equiv \frac{|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2}{|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2}.\tag{4}$$

The mixing-induced CP asymmetry is defined as

$$\begin{aligned}a_{cp}(t) &\equiv \frac{Br(\bar{B}^0(t) \rightarrow f) - Br(B^0(t) \rightarrow f)}{Br(\bar{B}^0(t) \rightarrow f) + Br(B^0(t) \rightarrow f)} \\ &= S \sin(\Delta m_B t) - C \cos(\Delta m_B t),\end{aligned}\tag{5}$$

where

$$S = \frac{Im\lambda}{|\lambda|^2 + 1}, \quad \text{and } \lambda = -e^{-2i\phi_d} \frac{\bar{\mathcal{A}}}{\mathcal{A}}, \quad (6)$$

with ϕ_d the weak phase appearing in $B^0 - \bar{B}^0$ mixing and $\phi_d = \beta$ in the SM. The coefficient C is related to the direct CP asymmetry by $C = -a_{cp}$. The latest data involving $B \rightarrow \eta^{(\prime)} K$ are summarized in Tab.I [49, 50, 51]

	CLEO	BaBar	Belle	WA
$Br(\eta \bar{K}^0)$	< 9.3	< 2.5	< 2.0	< 2.0
$Br(\eta K^-)$	$2.2_{-2.2}^{+2.8}$	$3.3 \pm 0.6 \pm 0.3$	$2.1 \pm 0.6 \pm 0.2$	2.6 ± 0.5
$Br(\eta' \bar{K}^0)$	$89_{-16}^{+18} \pm 9$	$67.4 \pm 3.3 \pm 3.3$	$68 \pm 10_{-8}^{+9}$	68.6 ± 4.2
$Br(\eta' K^-)$	$80_{-9}^{+10} \pm 7$	$68.9 \pm 2 \pm 3.2$	$78 \pm 6 \pm 9$	70.8 ± 3.4
$a_{cp}(\eta K^-)$		$-0.2 \pm 0.15 \pm 0.01$	$-0.49 \pm 0.31 \pm 0.07$	-0.25 ± 0.14
$a_{cp}(\eta' \bar{K}^0)$				(0.04 ± 0.08)
$a_{cp}(\eta' K^-)$	$0.03 \pm 0.12 \pm 0.02$	$0.033 \pm 0.028 \pm 0.005$	$-0.015 \pm 0.007 \pm 0.009$	0.027 ± 0.025
S'		$0.30 \pm 0.14 \pm 0.02$	$0.65 \pm 0.18 \pm 0.04$	0.43 ± 0.11

TABLE I: The latest world average of branching ratios (in unit of 10^{-6}), direct CP violations as well as mixing-induced CP violations for $B \rightarrow \eta K, \eta' K$ modes. The direct CP asymmetry of $\eta' \bar{K}^0$ comes from time-dependent CP asymmetry measurements of $\eta' K_S$.

It is well known that the unusually large branching ratios of $B \rightarrow \eta' K$ modes may require an enhancement of flavor singlet penguin diagrams \mathcal{S} , which possess another theoretical challenge and is still under extensive theoretical study (see, e.g.[52]). The flavour singlet contribution can be systematically calculated in QCD factorization, the results favour a smaller value with significant theoretical uncertainties[53]. However, for the purpose of extracting weak phases one needs only the ratios of decay rates between neutral and charged modes in which the penguin amplitudes cancel to a great extent, making the results insensitive to \mathcal{S} . We then define a ratio between neutral and charged decay rates as

$$R^{(\prime)} \equiv \frac{\tau_+}{\tau_0} \frac{Br(\eta^{(\prime)} \bar{K}^0)}{Br(\eta^{(\prime)} K^-)}, \quad (7)$$

The current data of $B \rightarrow \eta' K$ gives

$$R' = 1.04 \pm 0.08. \quad (8)$$

The corresponding ratio in ηK modes gives $R < 0.83$. The ratio between tree and penguin type diagrams are parameterized as

$$\zeta^{(\prime)} e^{i\delta^{(\prime)}} = \frac{\mathcal{C}}{\mathcal{P}_{\eta^{(\prime)}}} e^{i\gamma}, \quad \chi^{(\prime)} e^{i\omega^{(\prime)}} = \frac{\mathcal{T} + \mathcal{C}}{\mathcal{P}_{\eta^{(\prime)}}} e^{i\gamma}, \quad (9)$$

where $\zeta^{(\prime)}$ and $\chi^{(\prime)}$ are both real-valued. $\delta^{(\prime)}$ and $\omega^{(\prime)}$ are purely strong phases as the weak phase γ has been extracted from the definitions. We further define a ratio between color-suppressed and color-allowed tree diagrams

$$r e^{i\varphi} \equiv \frac{\zeta^{(\prime)} e^{i\delta^{(\prime)}}}{\chi^{(\prime)} e^{i\omega^{(\prime)}}} = \frac{\mathcal{C}}{\mathcal{T} + \mathcal{C}}, \quad (10)$$

with $r = |\zeta^{(\prime)}/\chi^{(\prime)}|$ and $\varphi = \delta^{(\prime)} - \omega^{(\prime)}$, which are common to both ηK and $\eta' K$ modes.

All the parameters can be solved numerically from the above equations. They can also be solved analytically to the leading order expansion of $\zeta^{(\prime)}$ and $\chi^{(\prime)}$. Taking the $\eta' K$ modes as an example, to the leading order of ζ' and ω' , the ratio of the decay rates is given by

$$R' \equiv 1 + \Delta R' \simeq 1 + 2\zeta' \left[\cos \delta' - \frac{1}{r} \cos(\delta' - \varphi) \right] \cos \gamma. \quad (11)$$

The two direct CP asymmetries are

$$a'_0 \equiv a_{cp}(\eta' \bar{K}^0) \simeq 2\zeta' \sin \delta' \sin \gamma, \quad (12)$$

$$a'_- \equiv a_{cp}(\eta' K^-) \simeq 2 \frac{\zeta'}{r} \sin(\delta' - \varphi) \sin \gamma. \quad (13)$$

The mixing-induced CP violation is found to be

$$S' \equiv S(\eta' K_S) \simeq \sin 2\beta + 2\zeta' \cos 2\beta \cos \delta' \sin \gamma. \quad (14)$$

In the above expressions, we use the primed quantities such as R' , a'_0 , a'_- and S' to denote ratio of decay rates, direct and mixing-induced CP asymmetries respectively in $\eta' K$ modes. For $B \rightarrow \eta K$ process, equations similar to Eq.(11)-(14) can be constructed with the substitution of primed quantities to be unprimed ones i.e R , a_0 , a_- and S etc. The Eqs.(11)-(14) together with the ones for ηK modes provide eight equations which constrain the eight parameters,

$$\zeta', \delta', \zeta, \delta, r, \varphi, \gamma \text{ and } \beta.$$

A simultaneous determination of γ and β will allow a reconstruction of the unitarity triangle from $\eta^{(\prime)} K$ modes alone.

Since great success has already been achieved in the measurement of $\sin 2\beta$ from $B \rightarrow J/\psi K_S$ in the two B -factories and the value obtained agrees remarkably with the one from global fits to all the indirect measurements such as neutral B and K meson mixing and semileptonic B decays etc, throughout this paper we shall take the value of [54, 55]

$$\sin 2\beta = 0.687 \pm 0.032 \quad (15)$$

from $B \rightarrow J/\psi K_S$ as input and focus on the determination of the less known weak phase γ in $\eta^{(\prime)}K$ modes.

Following this strategy, the value of r and φ are determined purely by direct CP asymmetries and β

$$\tan \varphi \simeq \frac{(a'_0 a_- - a_0 a'_-) \cos 2\beta}{a_-(S' - \sin 2\beta) - a'_-(S - \sin 2\beta)}, \quad (16)$$

and

$$r \simeq \frac{a'_0}{a'_-} \left(\cos \varphi - \frac{S' - \sin 2\beta}{a'_0 \cos 2\beta} \sin \varphi \right). \quad (17)$$

Note that the determination of φ requires CP asymmetry measurements for both ηK and $\eta' K$ modes. The solution to γ in terms of r , φ and β is found straight forwardly

$$\tan \gamma \simeq \frac{1}{r \Delta R'} \left[(r - \cos \varphi) \frac{S' - \sin 2\beta}{\cos 2\beta} - a'_0 \cdot \sin \varphi \right]. \quad (18)$$

Thus γ is determined up to discrete ambiguities. The above expression forms the base of the present paper. The weak phase γ does not depend on the ratio ζ' and χ' . It only depends on the ratio between tree type diagrams r and φ . The accuracy of γ depends heavily on the CP violation measurements. It also depends on the ratios of the decay rates R' . Note again that in this method the weak phase γ is determined within a closed subset of $\eta^{(\prime)}K$. No measurements from other modes are needed. In a typical case where φ is small and $r < \cos \varphi$, the second term in the right handed side of Eq.(18) is negligible, the sign of $\tan \gamma$ depends on the sign of $(S' - \sin 2\beta)/\Delta R'$. Thus a positive $\tan \gamma$ nontrivially requires $R' > 1$ since the current data prefer $S' - \sin 2\beta < 0$. The value of $\tan \gamma$ will be enhanced if r or $\Delta R'$ is very small.

The main source of the uncertainties comes from the SU(3) breaking between ηK and $\eta' K$ decay amplitudes. At present there is no robust estimates for SU(3) breaking effects. In the naive factorization approach the SU(3) breaking arises from two

difference pieces in $B \rightarrow \eta^{(\prime)} K$ amplitudes. One is proportional to the form factors $F_0^{B \rightarrow \eta}(m_B^2 - m_\eta^2)/F_0^{B \rightarrow \eta'}(m_B^2 - m_{\eta'}^2) \approx 1.16$ with $F_0^{B \rightarrow \eta^{(\prime)}}$ the form factor of $B \rightarrow \eta^{(\prime)}$ transition. The other one is proportional to the decay constants $f_\eta^u/f_{\eta'}^u \approx 1.22$. This gives an estimate that the SU(3) breaking effect is up to $\sim 20\%$. It needs to be emphasised that P_η and $P_{\eta'}$ are treated as two independent parameters not related by SU(3) symmetry. Note that the SU(3) symmetry could be broken in a more complicated way in the strong phase[56] and radiative corrections may give contributions not proportional to the decay constants [53]. The accuracy of r , φ and $\delta^{(\prime)}$ lies on the precision of a_{cp} to be measured from $\eta^{(\prime)} K$ modes. The branching ratios for $\eta' K$ are known to be large (a few $\times 10^{-5}$), while the ηK modes are expected to be an order of magnitude smaller due to it's flavor structure [57]. However, in the ηK modes the tree-penguin interferences could be stronger and the direct CP asymmetries could be more significant. With the increasing statistics in the two B -factories, the precision of $a_{cp}(\eta' K)$ will be improved. Higher precision measurements can be achieved in the future super- B factories [58].

III. IMPLICATIONS FROM THE LATEST DATA

The weak phase γ obtained from $\eta^{(\prime)} K$ modes can be compared with the one from other methods. The difference, if exists will shed light on the nonstandard contributions or possible new physics. At present, the data of the direct and mixing-induced CP asymmetries for $\eta \bar{K}^0$ are not yet available, one can not have a practical estimate of γ from Eq.(18). However, r and φ can be extracted from other modes or calculated theoretically. Taking r and φ as inputs, one can infer the value of γ from $\eta' K$ modes using the current data and compare it with the SM fit value. For illustrations, we consider two typical sets for the value of r and φ

- a) The values of r and φ are extracted from global $\pi\pi$ and πK fit based on flavor SU(3) symmetry. All the recent fits prefer a large \mathcal{C} [24, 25, 34, 35, 36, 59]. From an up to date fit in Ref.[25], one finds the following values

$$r = 0.56 \pm 0.05, \quad \varphi = (-33.2 \pm 6.3)^\circ. \quad (19)$$

The large r is driven by the observed large branching ratio of $\pi^0 \pi^0$. The value of r obtained in the $\pi\pi$ and πK fits can be directly used in $\eta' K$ as the leading SU(3) breaking effects cancel in the ratio between \mathcal{C} and \mathcal{T} .

- b) The values of r and φ are taken from QCD factorization calculations [4, 60], which prefers smaller values with considerable uncertainties. In numerical estimations we take the following typical values from the latest QCD factorization estimate [60]

$$r = 0.20 \pm 0.14, \quad \varphi = -(12 \pm 18)^\circ. \quad (20)$$

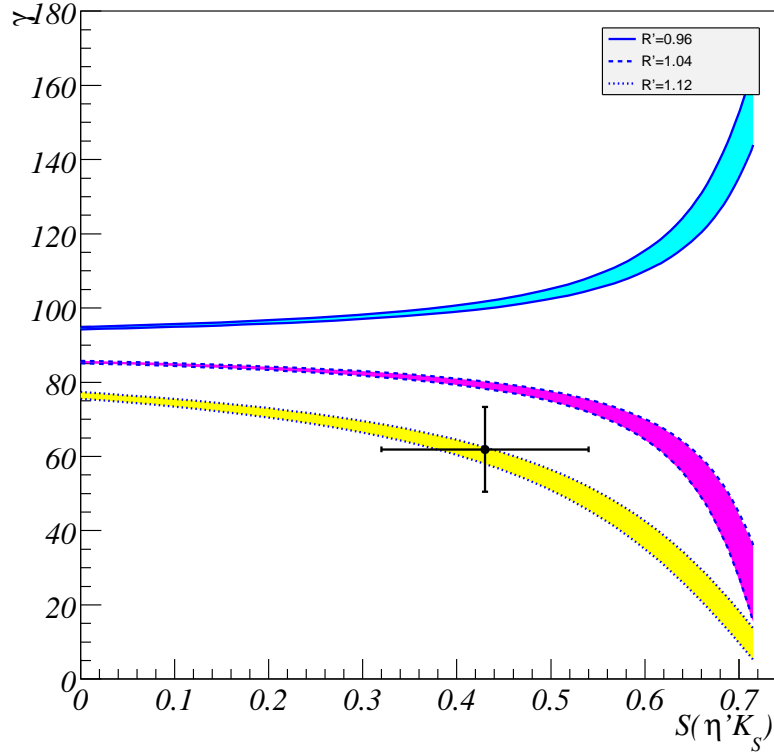


FIG. 1: Weak phase γ (in degree) as function of S' . The solid, dashed and dotted bands corresponds to $R' = 0.96, 1.04$, and 1.12 respectively. The cross indicates the current experimental measurements with the horizontal bar representing the data of S' and the vertical one representing the favored range of γ from global SM fit. The values of r and φ are taken from Eq.(19) with uncertainties taken into account.

In Fig.1. we plot γ as a function of S' , taking Eq.(19) as inputs for three different values of $R'=0.96, 1.04$ and 1.12 respectively, corresponding to the 1σ allowed range. The figure shows a strong dependence of γ on both S' and R' . For $R' < 1$, γ grows up with S'

increasing and is always larger than the best fitted value from global CKM fit. For $R' > 1$, it moves down to the opposite direction and reaches $\sim 60^\circ$ for $S' \simeq 0.5$. For $R' = 1$, $\tan \gamma$ becomes infinity which fix γ at $\sim 90^\circ$. The current data of R' can not definitely tell us if R' is greater or smaller than unity. To have a robust conclusion, higher precision data are urgently needed.

From Fig.1, one finds a overall consistency with the global SM fit. For S' and R' varying in the 1σ range, the value of γ is found to be

$$45^\circ \lesssim \gamma \lesssim 110^\circ. \quad (21)$$

The error is still significant and the center value gives a slightly large $\gamma \sim 78^\circ$. Note that some previous analyses found problems to coincide with a small S' [23, 61]. The difference mainly originates from the data used in the fits. In the present paper, we use the updated data while in the previous ones the old data of $Br(\eta' K^-) = 77.6 \pm 4.6$ and $Br(\eta' \bar{K}^0) = 65.2 \pm 6.2$ are used which corresponds to $R' \simeq 0.91$. As it is shown in Fig.1, a small $R' < 1$ will not make a good fit.

In Fig.2, a similar plot is made with the values of r and φ taken from Eq.(20). Comparing with Fig.1, one sees a smoother dependence on R' and S' , for a smaller $r = 0.20$ from Eq.(20) and R' , S' in the 1σ range, the value of γ is found to be confined in a narrow range of

$$85^\circ \lesssim \gamma \lesssim 95^\circ \quad (22)$$

Clearly, a large $\gamma \sim 90^\circ$ is favored in this case. The reason is that the smaller r enhances $\tan \gamma$, making the three curves closing to each other and forcing γ to be $\sim 90^\circ$. In this case γ can reach $\sim 60^\circ$ only for $S' = 0.6 \sim 0.7$, i.e. close to the $\sin 2\beta$ from $B \rightarrow J/\psi K_S$. One has to bear in mind that the measurement on S' is not very conclusive yet as there still exist discrepancy between Babar and Belle results [49, 50]. Using the PDG average method, the error should be enlarged by a factor of $\sqrt{\chi^2}$ which is the square root of the chi-square value of the average. This gives $S' = 0.43 \pm 0.17$. However, a large γ is still favored in the enlarged region. The theoretical prediction to S' based on QCD factorization prefer that S' is slightly greater than $\sin 2\beta$, $S' - \sin 2\beta \simeq 0.01$ [31, 32]. This remains to be tested in the future experiment.

It follows from the above results that if γ is indeed around 62° , a large r is favored by the current data of $\eta' K$ only, which is independent of the data of $\pi\pi$ and πK . Independent determination of the relative size of the color-suppressed tree diagram may provide us important

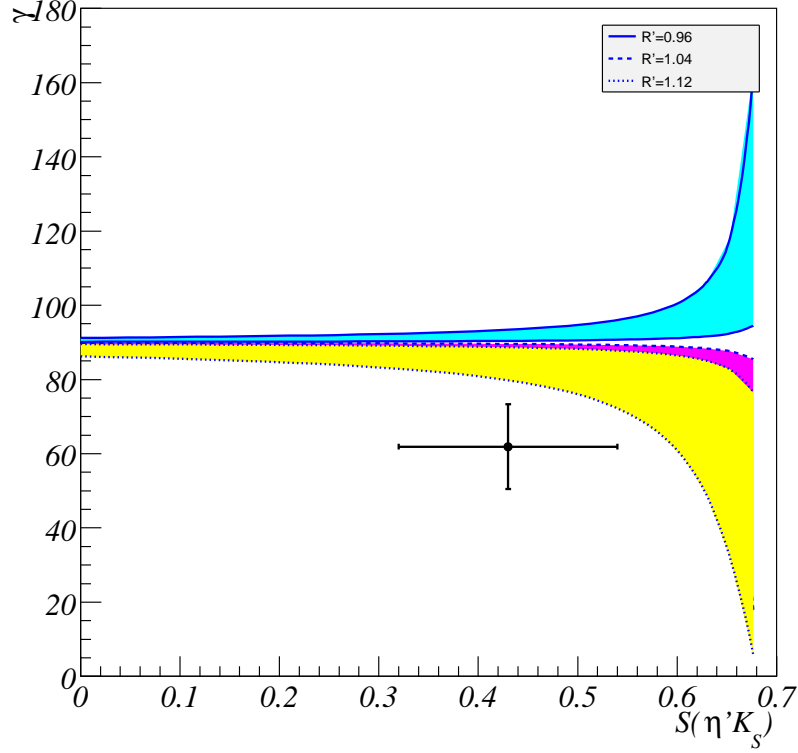


FIG. 2: The same as Fig.1 while the value of r and φ are taken from Eq.(20)

hints on it's origin. A possible explanation is that the extracted \mathcal{C} is an effective amplitude involving other important contributions such as: a large nonfactorizable W -exchanging diagram \mathcal{E} [26, 27, 28], a large penguin type diagram contribution through internal $c\bar{c}$ loops, i.e. the charming penguin [62, 63], large final state interactions [64, 65] etc. The exchange diagram \mathcal{E} only contributes to $\pi\pi$ modes and will not affect πK and $\eta' K$. The charming penguin always come together with the ordinary penguin diagrams. But the tree-penguin interferences are different in $\pi\pi$, πK and $\eta' K$. One can not expect a universal enhancement pattern of \mathcal{C} in all modes. The final state interaction is more process-dependent. Thus if the ratio r can be precisely determined independently from various subsets, it is possible to distinguish some of the explanations. For instance, if large r is confirmed in all the $\pi\pi$, πK and $\eta^{(\prime)} K$ modes, the first explanation will not be favored.

IV. NEW PHYSICS EFFECTS

We proceed to discuss the new physics contributions. When the weak phase β is taken as known from $B \rightarrow J/\psi K_S$, there are eight data points to constrain seven real parameters in $\eta^{(\prime)}K$ system. The nonzero degree-of-freedom allows one to make cross-checks for consistency or explore new physics contributions.

The new physics may affect the observables in two different ways. One is through modifying $B^0 - \bar{B}^0$ mixing which makes $\phi_d \neq \beta$. The consequence is that the mixing induced CP asymmetry for all the modes will be affected in the same manner, which is not very likely as the measurement of $\sin 2\beta$ from $J/\psi K_S$ agrees remarkably with all the indirect measurements of the unitarity triangle and so far no systematic deviations of $\sin 2\beta$ from it's global SM fit value are confirmed in other modes. The other way is that new physics contributes to decay amplitudes, most likely through $b \rightarrow s$ loop processes. In this case the modifications to direct and mixing-induced CP asymmetries will be process dependent.

Taking the $\eta'K$ modes as an example, we parameterize the new physics contribution to $b \rightarrow s$ penguin in the following form

$$\begin{aligned}\bar{\mathcal{A}}(\eta' \bar{K}^0) &= \frac{1}{\sqrt{6}} \mathcal{P}_{\eta'} \left[1 + \zeta' e^{i\delta'} + \xi_s e^{i(\delta_s + \phi_s)} \right], \\ \bar{\mathcal{A}}(\eta' K^-) &= \frac{1}{\sqrt{6}} \mathcal{P}_{\eta'} \left[1 + \chi' e^{i(\delta' - \varphi)} + \xi_s e^{i(\delta_s + \phi_s)} \right],\end{aligned}\tag{23}$$

where δ_s and ϕ_s are the strong and weak phases generated by new physics. It's relative size to $\mathcal{P}_{\eta'}$ is denoted by ξ_s . For simplicity, we assume that the new physics contribution respects the isospin symmetry under $u \leftrightarrow d$. This happens to the modes mainly contributing to the QCD penguins [66]. For any specific models such as the two-Higgs-doublet model [67, 68, 69, 70], the Z' model [71] etc. the relation between them is computable. In the presence of new physics, the expressions for CP asymmetries to the leading order are modified as follows

$$\begin{aligned}a'_0 &\simeq 2\zeta' \sin \delta' \sin \gamma - 2\xi_s \sin \delta_s \sin \phi_s, \\ a'_- &\simeq 2\chi' \sin(\delta' - \varphi) \sin \gamma - 2\xi_s \sin \delta_s \sin \phi_s.\end{aligned}\tag{24}$$

and the mixing-induced CP asymmetry is given by

$$S' \simeq \sin 2\beta + 2\zeta' \cos 2\beta \cos \delta' \sin \gamma - 2\xi_s \cos 2\beta \cos \delta_s \sin \phi_s.$$

Note that in this case R' is not affected as the new physics contributions to charged and neutral modes cancel. The difference between two direct CP asymmetries $a'_0 - a'_-$ is not

affected either. In the presence of new physics, the weak phase γ extracted from Eq.(18) will be an effective one denoted by $\tilde{\gamma}$, and is related to the true value of γ through

$$\begin{aligned}\tan \tilde{\gamma} &\equiv \frac{1}{r\Delta R'} \left[(r - \cos \varphi) \frac{S' - \sin 2\beta}{\cos 2\beta} - \sin \varphi \cdot a'_0 \right] \\ &\simeq \tan \gamma - 2 \frac{r \cos \delta_s - \cos(\delta_s - \varphi)}{r\Delta R'} \xi_s \sin \phi_s.\end{aligned}\quad (25)$$

Thus the deviation of the effective value $\tilde{\gamma}$ from the true γ is a measure of the new physics effects and which can be used to extract new physics parameters or distinguish different new physics models [72]. The true value of γ can be obtained from other measurements such as through $B \rightarrow DK$ [73] or from global CKM fits. The new physics effects will be enhanced if the deviation of R' from unity is tiny. As the current data give a central value of $R' \simeq 1.04$, the effective $\tilde{\gamma}$ is very sensitive to new physics. If the true value of γ is indeed around 62° , for typical values of r and φ taken from Eq.(19) and $R' = 1.04$, the enhancement factor is about ~ 50 . As a consequence, significant difference of a few tens degree between $\tilde{\gamma}$ and γ is possible for $\xi_s \sin \phi_s \sim 0.1$.

It has been argued recently that in general the new physics will not generate significant relative strong phases as the strong phases mainly originate from the long-distance rescatterings of the final states while new physics contributes only to short-distant part [74]. In the case that the new physics strong phase δ_s is negligible, the combined new physics parameter $\xi_s \sin \phi_s$ can be directly extracted. As an illustration, we take the central value of $r = 0.56$ and $\varphi = -33^\circ$ from Eq.(19) and R' in the 1σ range, which gives

$$0 \lesssim \xi_s \sin \phi_s \lesssim 0.25. \quad (26)$$

It follows that for a large r , the current data marginally agree with the SM, and the new physics receives only an upper bound.

For a smaller value of $r = 0.2$ and $\varphi = -12^\circ$ in Eq.(20), a positive signal of nonzero $\xi_s \sin \phi_s$ is found

$$0.15 \lesssim \xi_s \sin \phi_s \lesssim 0.19, \quad (27)$$

which demonstrates that the $\eta^{(\prime)}K$ mode provide a good avenue to explore new physics contributions. Needless to say that the current experimental status is not conclusive yet and one can not draw a robust conclusion on the presence of new physics. The advantage

of using Eq.(25) in $\eta'K$ modes to probe new physics is that besides new physics parameters the difference between the effective and the true γ only depends on the hadronic parameters r and φ . The knowledge of the tree-penguin ratio $\zeta^{(\prime)}$ and $\chi^{(\prime)}$ are not needed. Comparing with probing new physics through $B_s \rightarrow KK$, although the flavor structure in $B_s \rightarrow KK$ is simpler, the tree-penguin interference can not be avoid and one has to combine it with $B \rightarrow \pi\pi$ where additional assumptions on new physics effects in $b \rightarrow d$ penguin have to be made[75].

V. CONCLUSION

In summary, we have present a method for an independent determination of the weak phase γ from $B \rightarrow \eta^{(\prime)}K$ alone, which makes use of measurements of all the direct and mixing-induced CP asymmetries. The value of γ extracted from $\eta^{(\prime)}K$ may be compared with the ones from other modes. The possible discrepancy may help us to understand the current puzzles in charmless B decays. We have taken two sets of the ratio \mathcal{C}/\mathcal{T} as inputs to analysis the implications of the recent data on $\eta'K$ modes. One is from from global $\pi\pi$, πK and KK fits which leads to a $45^\circ \lesssim \gamma \lesssim 110^\circ$ in agreement with the SM fit value. The other is from QCD factorization calculations which makes γ around 90° . Within the SM, it implies that a large \mathcal{C} is independently favored in $\eta'K$ modes. New physics beyond SM can be singled out if γ obtained in $\eta'K$ modes is significantly different than the ones from other decay modes or other approaches. The value of γ obtained from $\eta'K$ are found to be sensitive to new physics contributions and can be used to extract new physics parameters if the new physics does not carry significant new strong phases.

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